

Frequency Multipliers

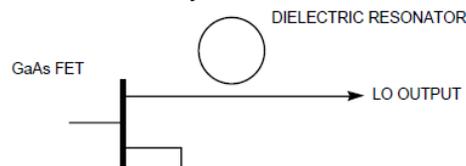
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There are few approaches how to generate a high frequency signal for microwaves frequencies.

Direct Signal Generation -

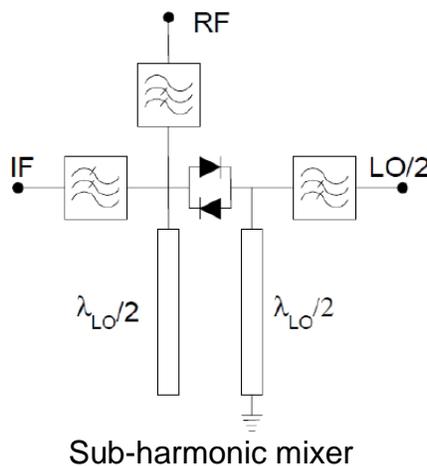
First approach is to generate the high frequency directly, at the fundamental, using an oscillator tuned on the desired frequency. Few sensitive issues appear here due to high working frequency as, stability, jitter, phase noise, pulling, pushing, low output power, and cost of the active component to meet the performances.

A FET oscillator may be stabilized by a dielectric resonator. Problems may involve in this situation are: phase noise, frequency stability and accuracy.



Sub-Harmonic Mixer -

Another approach how to minimize the issues of a high frequency oscillator is to use a Sub-Harmonic mixer.

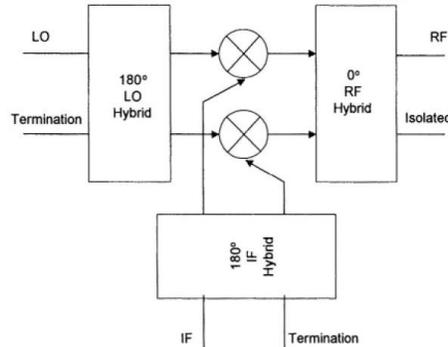


- Sub-harmonic mixers are useful at higher frequencies when it can be difficult to produce a suitable LO signal. They have the LO input at frequency = LO/n.
- Sub-harmonic mixers use anti-parallel diode pairs and they produce most of their power at “odd” products of the input signals. Even products are rejected due to the I-V characteristics of the diodes.
- Attenuation of even harmonics is determined by diodes “balance”. The diode “matching” is critical in this type of mixers.
- The short circuit $\lambda_{LO}/2$ stub at the LO port is a quarter of a wavelength long at the input frequency of LO/2 and so is open circuit. However, at RF frequency this stub is approximately a half wavelength long, so providing a short circuit to the RF signal.
- At the RF input the open circuit $\lambda_{LO}/2$ stub presents a good open circuit to the RF but is a quarter wavelength long at the frequency LO/2 and so is short circuit.

Up-Conversion Mixer -

The third option to generate a high frequency signal is to use an up converter. The design of an up converter has typically received much less attention in terms of design methodology than down converter design, which is common approach in most of the receiver designs. There are some aspects to up converter design which are not relevant to down converters, and vice versa.

- An up-conversion mixer requires high linearity and low noise to minimize the amount of spurious power spread into adjacent channels.
Have to take careful attention at LO amplitude, and LO-to-RF isolation.
- A good approach for an up-conversion mixer is the balanced mixer which provides good common-mode rejection to suppress LO feed-through and good linearity.
- The LO level should provide a reasonable compromise between conversion gain and LO power, but should not limit the 1 dB gain-compression input voltage.



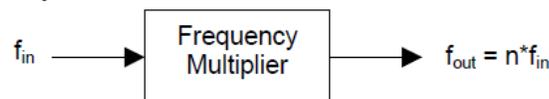
Balanced up-conversion mixer

Frequency Multipliers –

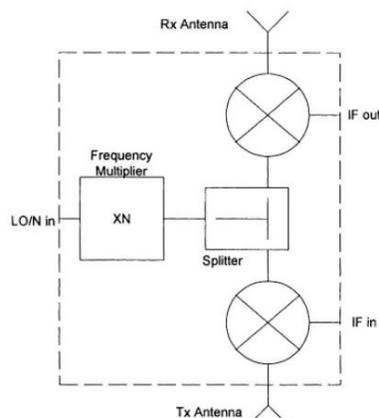
Another alternative method to generate high frequency signal power with low phase noise is to generate a high-quality lower frequency signal and employ a **frequency multiplier** to deliver the high frequency output at the desired frequency. This approach is the subject of this paper.

Frequency multipliers will always be a way of generating the highest frequencies.

- A **frequency multiplier** has the property that the frequency of the output signal has an integer multiple of the input frequency.



This approach is commonly adopted in microwave transceivers.



Frequency multiplier based microwave transceiver block diagram

Even if a multiplier introduces no Phase Noise of its own, the process of frequency multiplication even by an ideal, noiseless multiplier, inevitably increases the Phase Noise.

- The reason for this unfortunate characteristic is that a **frequency multiplier** is in fact a **phase multiplier**, so it multiplies the phase deviations as well as the frequency of the input signal.
- A square-wave contains odd harmonics. However, by varying the duty cycle of the waveform, so that rectangular-wave results, even order harmonic content can be introduced.
- The 2nd harmonic content of a rectangular-wave peaks when the duty cycle is 25%, and a 3rd harmonic peaks when duty cycle peaks 16%.
- The minimum Carrier-to-Noise degradation, ΔCNR , in decibels, caused by an ideal frequency multiplier is:

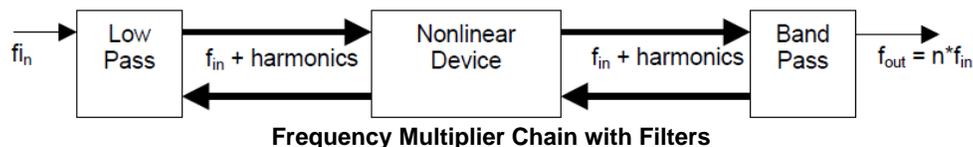
$$\Delta\text{CNR}_{[\text{dB}]} = 20 \cdot \text{LOG} (N) \quad \text{where } N \text{ is the multiplication factor.}$$

- Thus, a frequency doubler ($N=2$) degrades CNR at the input signal by at least 6dB and a quadrupler ($N=4$) degrades CNR by at least 12dB.

Multiplying a very stable low-frequency reference signal can still produce signals with better Phase Noise than producing them directly in the microwave frequency range.

- For example typical Phase Noise of a 10 MHz Crystal Oscillator is: -170 dBc/Hz @ 100 kHz offset.
- Using a multiplier chain ($10 \times 24 = 240$) to get a 2.4 GHz signal, degrades this Phase Noise by $20 \cdot \text{LOG}(240) = 48 \text{ dB}$, yielding: $-170 \text{ dBc/Hz} + 48 \text{ dB} = -122 \text{ dBc/Hz}$ @ 100 kHz offset.
- Compare this Phase Noise to a standard LC-tank oscillator working directly at 2.4 GHz, which has a typical Phase Noise of -100dBc/Hz @ 100 kHz offset.

A **frequency multiplier** circuit should contain a nonlinear device and filters that enable to select the desired component at the output and separate the source from the generated harmonics.



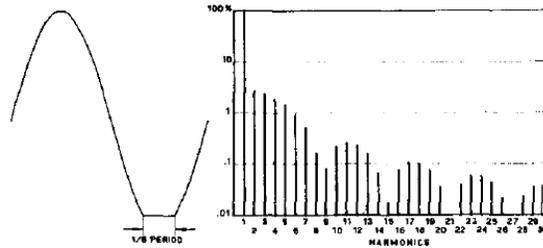
- The nonlinear device will produce voltages of higher order from the current of the first harmonic. One of these voltages is of the desired order and will be allowed to exit through the band-pass filter.
- Low-pass and band-pass filters will present high impedance to all unwanted harmonic voltages.
- But it turns out that if we allow the currents of the other harmonics to flow, the intermodulation products of those harmonics will contribute to the desired harmonic of the output frequency. That means we should try to short the currents of the non-desired harmonics.
- As we want to deliver as much power as possible to the load the frequency multiplier should be matched at the input (for the input frequency) and at the output (for the output frequency).

- A signal of pure sine waves contains only its fundamental frequency.

Any departure from this sine-wave pattern, no matter how small, is due to the presence of additional frequencies that are multiples (harmonics) of the fundamental frequency.

If this non-sinusoidal wave can be given an exact mathematical description, the amplitude and phase of each harmonic frequency it contains may be calculated.

For example, an amplifier that is driven slightly beyond the cutoff point will slice off the tip of the loop.

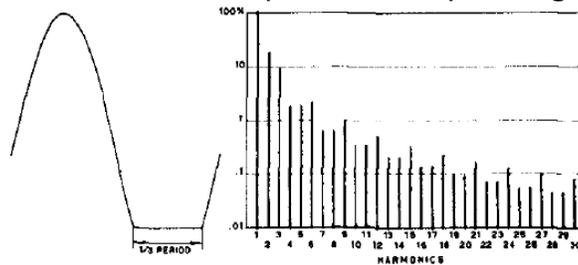


Negative clipping of the sine-wave (1/8 of the period)

An analysis will show that this deformation of the sine-wave gives rise to an endless number of harmonics, with amplitudes that tend to decrease (not uniform) with increase of frequency.

If an amplifier is driven into cutoff for a third of the duration of a period, in this case harmonic content is maximum for every harmonic divisible by three.

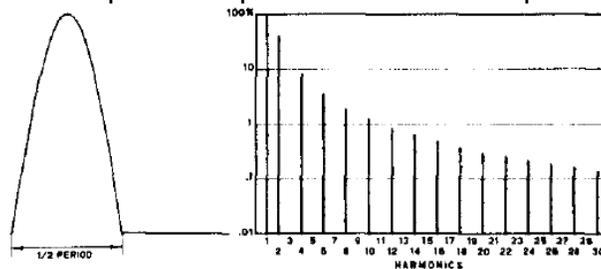
Peculiarly, the two intervening harmonics have amplitudes of equal magnitude.



Negative clipping of the sine-wave (1/3 of the period)

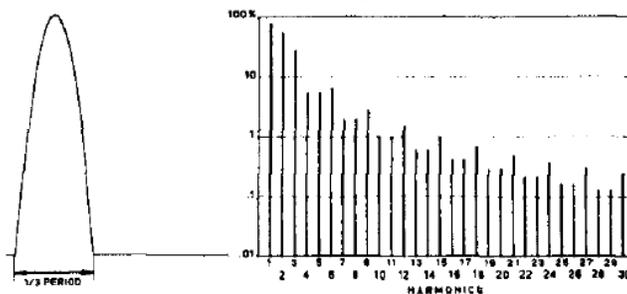
In case where the lower excursion of the sine wave has been clipped off entirely, (as a rectified half wave), every harmonic with an uneven number has disappeared.

The fundamental frequency has an amplitude equal to the actual amplitude of the half wave.



Negative clipping of the sine-wave (1/2 of the period)

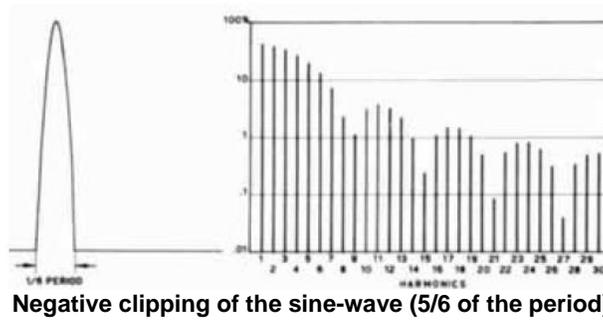
Next case shows a sine wave sliced off even more, so that only a third of the period is left. The envelope over the harmonic columns shows a pattern much like situation above, but the fundamental frequency has lower amplitude and higher harmonics, so have larger amplitudes than those of situation above.



Negative clipping of the sine-wave (2/3 of the period)

If the sine-wave is sliced off so much that only one-sixth of the period remains, the fundamental frequency has an amplitude of only 43% of the curve but the harmonics are quite prominent.

In the plot below the harmonic amplitude shows a wave pattern with minima at the 9th, 15th, 21st and 27th harmonic.



Looking to the all above plots we can see that we get the maximum 2nd harmonic level when slicing off two-thirds of the sine-wave which would give better 2nd harmonic performance than any of the other clipped waveforms pictured.

- Thus, for the highest 2nd harmonic content, 66% of the sine-wave (2/3 of the period) must be clipped off. This represents a conduction angle of about 119° which provides a 2nd harmonic amplitude of 55% of the basic curve's amplitude.
- If frequency tripling is wished (higher 3rd harmonic), the horizontal part of the curve (that is, the duration of the cutoff) should be in the neighborhood of three-quarters of the total period.

To obtain higher order frequency multiplication we can cascade several multipliers. This can increase conversion efficiency but also increases complexity.

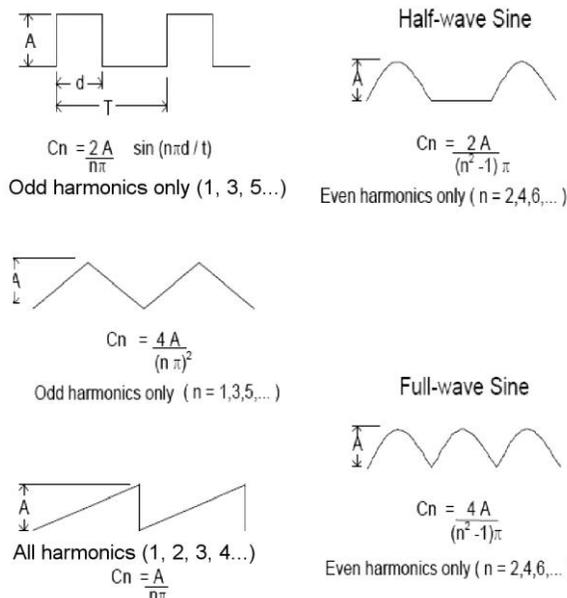
There are different possibilities concerning the nonlinear device:

- We need a device with a nonlinear characteristic in order to produce higher order harmonics.
- The nonlinear characteristic might be a nonlinear I-V or C-V relationship.
- Usually wideband multipliers use a nonlinear I-V characteristic, but when we want to design a frequency multiplier with high efficiency, and not high bandwidth, we prefer the nonlinear C-V characteristic. For example a varactor diode has a nonlinear C-V characteristic.

Frequency Multipliers Waveforms

Any non-sinewave repetitive waveform contains energy at harmonics of the fundamental frequency.

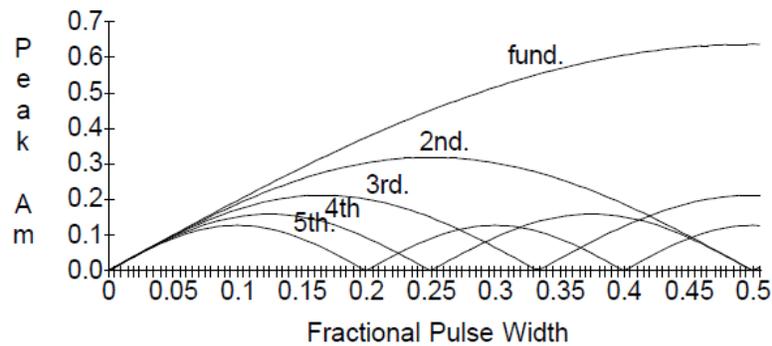
The task is to create a non-linear circuit that produces a waveform with significant signal strength at the desired harmonics. Figure below shows the amplitude terms (peak value of the nth harmonic sine wave) for various waveforms.



Harmonic amplitude terms for various waveforms (C. Wenzel)

- Can be seen that waveforms with fast edges have larger high frequency harmonics.
- Harmonics without vertical edges have n^2 in the denominator, but the waveforms with fast edges only have n in the denominator.
- The timing (duty-cycle) between the positive and negative edges of a pulse determines which harmonics are emphasized. For example, a 50% duty-cycle square-wave has only odd harmonics. In this situation the timing is wrong for the buildup of even-harmonic energy, but a 25% duty-cycle contains large even harmonics: the edges occur at the right time to reinforce certain even harmonics.

Figure below shows the harmonic content of a square pulse as a function of its duty-cycle.



Square Pulse Harmonic content vs Duty-Cycle (C. Wenzel)

As was mentioned before the chart suggests that the most 2nd harmonic energy will be generated when the duty-cycle is 25%. But it can also be seen that if the duty-cycle is increased to 33% then the third harmonic drops to zero which could simplify output filtering with little drop in the desired 2nd harmonic.

Frequency Multipliers Characteristics

- **Conversion Loss and Maximum Input Signal Power**

Semiconductor diodes used in microwave frequency multipliers are essentially lossy passive devices and for this reason they dissipate energy. Embedding circuits also dissipate energy. As a result, multiplier's input/output power conversion efficiency is less than unity.

Conversion Loss used to characterize microwave frequency multiplier's conversion efficiency is defined as the ratio of the available source power P_{in_source} to the output harmonic power $P_{out_harmonic}$ delivered to the load.

Conversion Efficiency is defined as the ratio of the output power P_{out} delivered to the load to the available power of the input source P_{in} , and usually is expressed in percent.

The goal of the circuit design is to minimize the conversion loss (or maximize the conversion efficiency) for a given device and input/output frequencies.

When get low conversion efficiency, virtually all the input power is dissipated in the nonlinear element.

The **maximum input power** is limited by the device power handling capability and must be clearly stated when specifying a frequency multiplier.

- **Source and Load Impedance**

One of the conditions for a diode frequency multiplier to achieve minimum conversion loss is that **optimum source** and **load impedance** should be provided to the diode.

The **source impedance** should be very close to the complex conjugate of the multiplier input impedance Z_{in} to minimize reflection loss at the input.

The load impedance should be equal to the optimum load value, otherwise leads to an increased conversion loss or decreased output power.

- **Bandwidth**

BW represents the output or input frequency range over which conversion loss is in the specified limits.

- **Harmonics**

A nonlinear device produces undesired harmonics along with the desired ones, and this might affect the performance of the system where the multiplier is used.

- **Noise Conversion**

In all practical situations the resulting noise sidebands are subject of frequency conversion together with the carrier. The multiplier devices add their own noise, and is important to predict the resulting output noise spectrum.

- **Phase Noise Conversion**

All frequency multipliers will increase the phase noise by the same factor (N) that they multiply, because frequency and phase are both multiplied. In dB this would be $20 \log N$.

Diode Frequency Multipliers

Diode frequency multipliers can be generally classified as being of **varistor** (Schottky barrier diode) or **varactor** type.

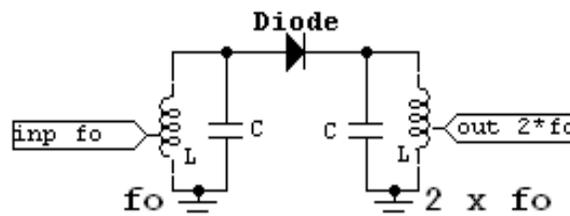
In the first case, frequency multiplication is performed by a nonlinear resistance or conductance with consequent poor conversion efficiency but a very large potential bandwidth.

In the **varactor type** multiplier, a nonlinear reactive element (with nonlinear capacitance) is used.

Varactor reactive type multipliers have high potential conversion efficiency (due to almost zero series resistance), needs very low drive power levels, but exhibit a narrow bandwidth and a high sensitivity to operating conditions, and sometimes stability problems. Because the frequency multiplication is based on a nonlinear reactance, these circuits have tuned input and output circuits and often tuned idler circuits as well. In theory, a cascade of low-order multipliers usually has greater efficiency than a single high-order multiplier, but must consider the additional losses in cascading two multipliers (it is invariably necessary to use an isolator between them), and especially the additional cost.

Resistive (Varistor) Frequency Multipliers

- Resistive frequency multipliers use the nonlinear I-V characteristic of a Schottky-barrier diode to distort a sinusoidal waveform. This distortion generates harmonics.
- The more is distorting the input sinusoid, the greater the harmonic currents in the diode, but the maximum still not very great because resistive frequency multipliers are not very efficient.
- In theory a diode doublers have 6dB conversion loss ($1/N^2$) but in reality, the conversion loss is about 10dB and there is no reason to make higher-harmonic resistive multipliers.
- The advantage of resistive multipliers is, they are very broadband.



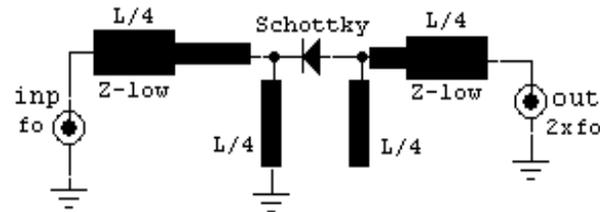
Simplified model of a Resistive (diode) Frequency Doubler

The parallel LC resonators are ideal because they short-circuit the diode at the unwanted harmonics, decoupling the input from the output, and put the diode in parallel with the input at the fundamental frequency and in parallel with the output at the second harmonic.

The inductor can be tapped to optimize the source and load impedances of the diode.

The **frequency doubler** using microstrip lines presented below is suitable for microwave frequencies.

- The circuit use a $\lambda/4$ at f_0 , short-circuited through a stub at the input side of the Schottky diode (which is equivalent to $\lambda/2$ at $2xf_0$), which is used to create a short-circuit at $2xf_0$ to prevent the output power generated in the diode from traveling backward.
- Similarly use a $\lambda/4$ at f_0 open-ended stub at the output side, which creates an RF short at f_0 and causes the input signal penetrating through the diode to be reflected back to the diode.
- A section of the transmission line is used as an inductor to resonate the diode junction capacitance.
- The $\lambda/4$ impedance transformers at the input and output are used to transform 50 ohms source and load to optimum diode impedance terminations.



Microwave Microstrip Frequency Doubler

Varactor Diode Frequency Multipliers

A nonlinear reactance also can distort the sinusoidal signal.

- The pros and cons of varactor multiplier are the opposite of those of resistive multiplier.
- A varactor is capable of higher efficiency and higher power than a resistive multiplier, theoretically 100% for all harmonics, but they are very narrowband.
- A design issue of varactor multipliers is they are extreme sensitive to almost every parameter of the circuit, and small changes in the circuit parameters (tuning reactances, bias voltages, input power level, etc) change the output power.
- Making a varactor multiplier work (and keep working) needs a lot of empirical tuning.
- Varactor diode frequency multipliers in general generate very little noise (phase- as well as amplitude noise). The only noise source is the thermal noise of the series resistance of the varactor and the circuit loss resistances.
- The power capability of a varactor multiplier is limited by the device's break-down.
- The varactor always has a parasitic resistance in series, which dissipates power.

In order to minimize the loss power, one would tend to present an open for all the undesired harmonics, resulting in zero current and therefore no loss.

At the example of the pure square-law diode we see that it produces only a 2nd order harmonic directly. This is the reason to present a short to the undesired (intermediate) harmonics.

- The shorting circuits are called idlers.
- Without idlers the varactor multiplier does not generate harmonics efficiently beyond the 2nd harmonic.
- If a current at the 2nd harmonic is prohibited, we don't get the desired higher order harmonics.
- If current is allowed at the 2nd harmonic, it will mix with the first harmonic and generate therefore higher order harmonics.
- A varactor tripler (x3) can be obtained only with a second harmonic idler.
- A varactor quadrupler (x4) could have a 2nd harmonic idler, or both a 2nd harmonic and a 3rd harmonic idler.
- A varactor quintupler (x5) would likely have at least 2nd and 3rd harmonic idlers.

Idlers are usually realized as short-circuit resonators that are separate from the input and output matching circuits.

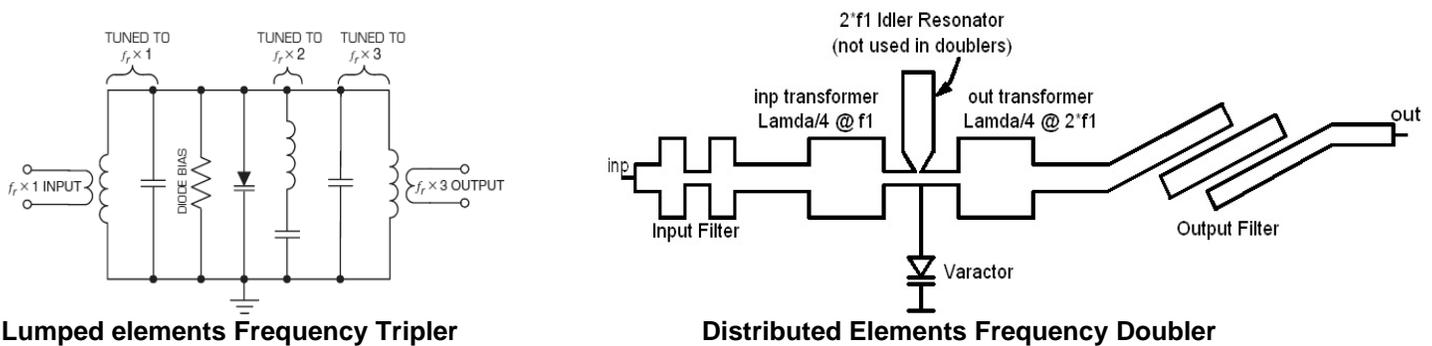
In practice, idlers are usually realized by a series resonance that is chosen more for its convenience than for high performance.

- Frequently, the series resonance of the varactor's package is used as an idler at high frequencies, and tuning elements are often included to tune the resonance precisely to the desired harmonic.

- To minimize power dissipation and thus to obtain high efficiency, is essential to use high unloaded Q (low-loss) idler resonators.
- Both phase noise and amplitude noise are strongly dependent on the level of the input signal pumping the diode.
- Varactor frequency multipliers are relative unstable. Their instability is a kind of chaotic process, not a simple oscillation.

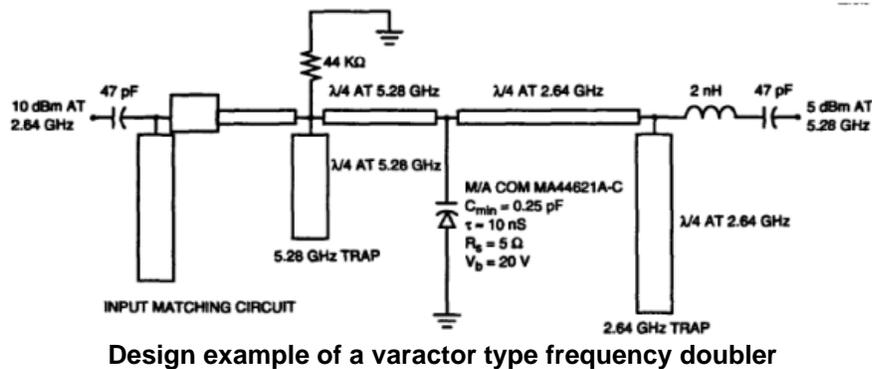
Controlling the broadband embedding impedance characteristic very carefully is the best way to insure good stability. In particular, the input source and output load must be linear and not vary with input or output level. One must not drive a mixer's LO port directly from a multiplier, or the multiplier directly from another multiplier; an isolator should be used. The input and output networks must not have any spurious resonances.

Introducing a resistor in the diode's DC return path, this current can be used to bias the diode. The resistor also helps to reduce the sensitivity of the output power level to the input power level; as input drive is increased, the resulting increase in DC current further reverse-biases the diode, reducing the multiplier's efficiency and leveling the output power. The design of the bias circuit often has a strong effect on stability. Low frequency resonances in the bias circuit are a common cause of instability.



Lumped elements Frequency Tripler

Distributed Elements Frequency Doubler



Design example of a varactor type frequency doubler

In example above with an input power of +10dBm, it has an efficiency of 32%. Much of the loss is likely due to the microstrip lines in the circuit and in the test fixture used to test the packaged circuit.

A variant of varactors are Schottky-Barrier varactor diodes which can obtain output frequencies of up to several hundred of GHz.

- One of the most important advantages of Schottky-Barrier based multipliers is the generation of odd harmonics without filtering the even ones.
- This capability is based on the symmetry of the electrical characteristics for unbiased devices. Thus, the load impedances for even harmonics have no effect on the efficiency characteristics.
- Any general analysis of varactor multipliers must consider the varied nature of the voltage-capacitance characteristic and the effects of forward conduction, and the circuit configuration or parameters representing circuit losses must be included.
- Generally, varactors are biased in one of two ways: fixed-bias or self-bias. In most biasing circuits a relatively large resistor is used to reject the RF currents. When a fixed voltage is applied and slight forward conduction is allowed in the varactor, the bias voltage is

actually offset by the voltage drop in the bias resistor. With this arrangement the bias is actually a combination of fixed and self-biases. While it is possible to arrange circuits for pure fixed bias, there is no special advantage to this configuration. In the self-bias arrangement, a large resistor is connected from the varactor to ground.

The bias voltage is obtained by a small rectified current resulting from signal swing into the forward region. One great advantage of the self-biased circuit is that the multiplier is, with this arrangement, completely passive.

Step Recovery Diode (SRD) and PIN Diode Frequency Multipliers

Step Recovery Diodes (also called snap-off diodes) are based on a PIN configuration.

They are commonly employed in the design of frequency multipliers of high order.

Step Recovery Diodes have relatively little capacitance change under reverse bias and are used for higher efficiency applications.

A Step Recovery Diode has two operating states. With forward bias it looks like a large capacitor, or as low impedance. Under reverse bias it looks like a small capacitor, or as high impedance.

- The change from low impedance to high impedance takes place quickly, in a time interval called diode transition time. The change produces a narrow pulse of voltage which is equivalent to a number of frequencies which are multiples of the input frequency.
- The highest frequency is limited by the narrowness of the pulse which is determined by the transition time.

A conventional step recovery diode multiplier consists of a diode, a biasing resistor, and matching filters at input and output. The output filter reflects the un-tuned harmonics back to the diode where they mix to form additional power at the tuned frequency.

- Step Recovery Diodes do not require idler circuits to enhance efficiency (as varactors).
- The SRD multiplier is a reactive multiplier and theoretically doesn't have the efficiency limitation ($1/N^2$) as resistive multipliers.
- In the design of high-order frequency multipliers, the efficiency of Step Recovery Diodes is much higher than that of varactor diodes. There is, however, a limit to the output frequency of the multiplier circuit.

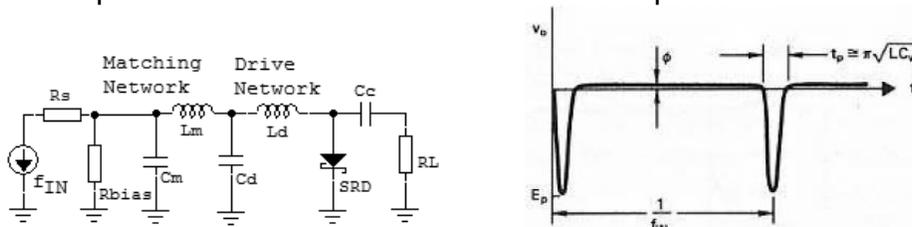
SRD Multiplier Design Procedure

Before designing the multiplier, few system design requirements should be known as: input frequency, output frequency, input power, output power, and bandwidth.

Based on this information have to follow few design procedures as: diode selection, impulse generator design, output resonant circuit design.

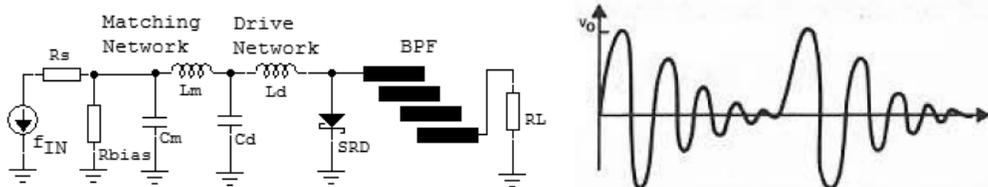
- Diode selection implies few important characteristics of the diode as:
 - Breakdown Voltage V_{BR} which determines the maximum amplitude and the energy of the impulse $U_C = \frac{1}{2} (C_{VR} * E_P^2)$
 - Reverse Bias Capacitance C_{VR} , which in addition to determining the energy in the impulse, also determines the impedance level of the ringing line. Usually is specified at -10V bias.
 - Series Resistance R_S determines the loss that will occur in the ringing line and the diode input circuit.
 - Minority Carrier Lifetime T determines the loss that occurs during forward charge storage due to carrier recombination as well as the value of the bias resistance R_B
 - Transition Time t_p determines the ability of the diode to form the required impulse width and sets the upper output frequency limit of the multiplier $t_p = \pi * \text{SQRT}(L * C_{VR})$
 - Package Parasitic Inductance L_P determines the proportion of the energy in the total drive inductance that is not transferred to the ringing circuit.
 - Thermal Resistance determines the amount of power that can be dissipated in the diode before the junction temperature reached a maximum safe value.

- When the output of the multiplier is terminated in a load resistance R_L , it forms a broadband multiplier and its output waveform is associated to a comb spectrum.



Broadband SRD Multiplier and Output Waveform

- When the output of the multiplier is terminated in a resonant network (band pass filter) it forms a narrow band multiplier, and the output level has the same energy but now is concentrated around the resonant frequency $f_{OUT} = n \cdot f_{IN}$



Narrowband SRD Multiplier (microstrip BPF) and Output Waveform

Biasing the Step Recovery Diode Multiplier

For maximum efficiency the sudden change of diode resistance should occur at the negative peak of the input waveform. This can happen by providing negative DC bias to the diode to set the time when conduction starts during the position portion of the input signal.

Bias voltage can be provided using a resistor across the input circuit, so the rectified DC current from the diode flows through the bias resistor to generate the negative bias voltage.

Equation for the proper value of the bias resistor R_B is:

$$R_B = (2 \cdot T) / (\pi \cdot N^2 \cdot C_{VR}) \text{ } [\Omega]$$

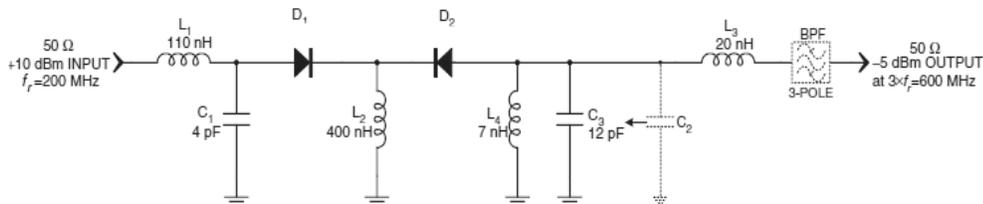
where T is carrier lifetime, N is the multiplication factor, and C_{VR} is the diode capacitance.

Ex1: If the lifetime T is $100 \cdot 10^{-9}$ seconds, the multiplication factor $N=2$ (frequency doubler), and diode capacitance $C_{VR} = 3\text{pF}$, the bias resistor should be $R_B = 5307\Omega$

Ex2: If the lifetime T is $100 \cdot 10^{-9}$ seconds, the multiplication factor $N=3$ (frequency tripler), and diode capacitance $C_{VR} = 3\text{pF}$, the bias resistor should be $R_B = 2359\Omega$

- Temperature increases the lifetime T of step recovery diodes about $0.5\% / ^\circ\text{C}$.

This issue can be compensated using a silicon resistor (sensistor), which actually is a heavily doped semiconductor with a positive temperature coefficient (the same as $0.5\% / ^\circ\text{C}$)

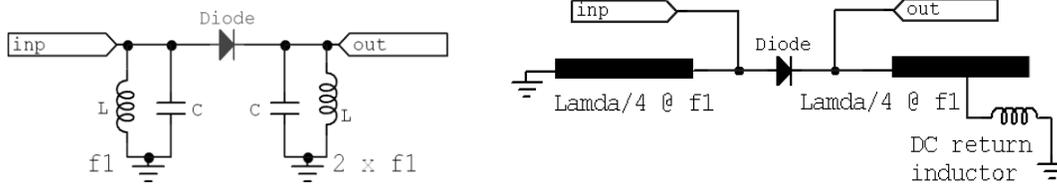


Frequency Tripler using Step Recovery Diodes

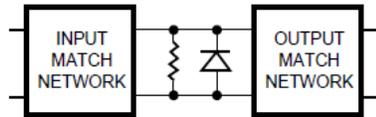
Single PIN Diode multiplier is useful mainly for low-cost or high frequency waveguide structures where fundamental frequency is easy to reject. A single diode multiplier has the advantage of easy to provide DC bias to it, which will help optimizing the multiplier.

A conventional PIN diode multiplier can use one diode or an anti-parallel pair of diodes.

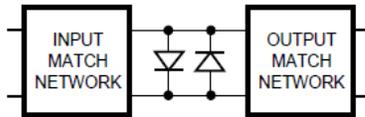
- The additional diode results in the suppression of even order products, the enhancement of odd order products, and the elimination of the bias resistor.



Single diode multipliers – lumped and distributed elements



Single Diode Multiplier

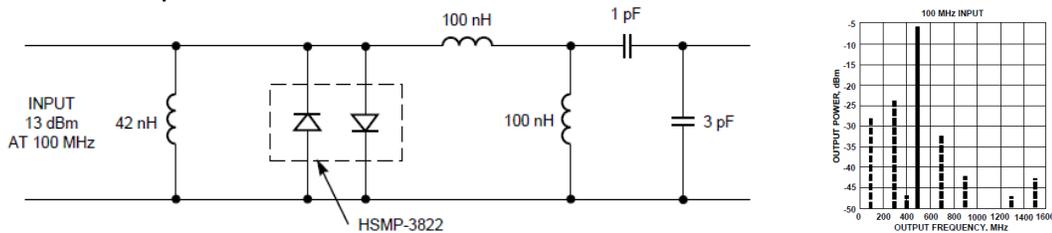


Anti-Parallel pair of Diodes

Balanced PIN Diode Multipliers have significant advantages compared to single-ended multipliers; the most important are increased output power and inherent rejection of the fundamental frequency and of certain unwanted harmonics.

- The input or load impedance of a balanced multiplier in some cases differs by a factor of two from that of a single-diode multiplier; therefore, a balanced multiplier sometimes provides more satisfactory input or load impedance.

The antiparallel diode connection is probably the simplest form of a balanced multiplier; it rejects even harmonics of the input frequency and consequently can be used only as an odd-order multiplier. In an antiparallel-diode multiplier, each diode effectively short circuits the other at the second harmonic, so each diode acts as a type of idler for the other. This circuit does not reject the fundamental frequency, however, so it requires an output filter.

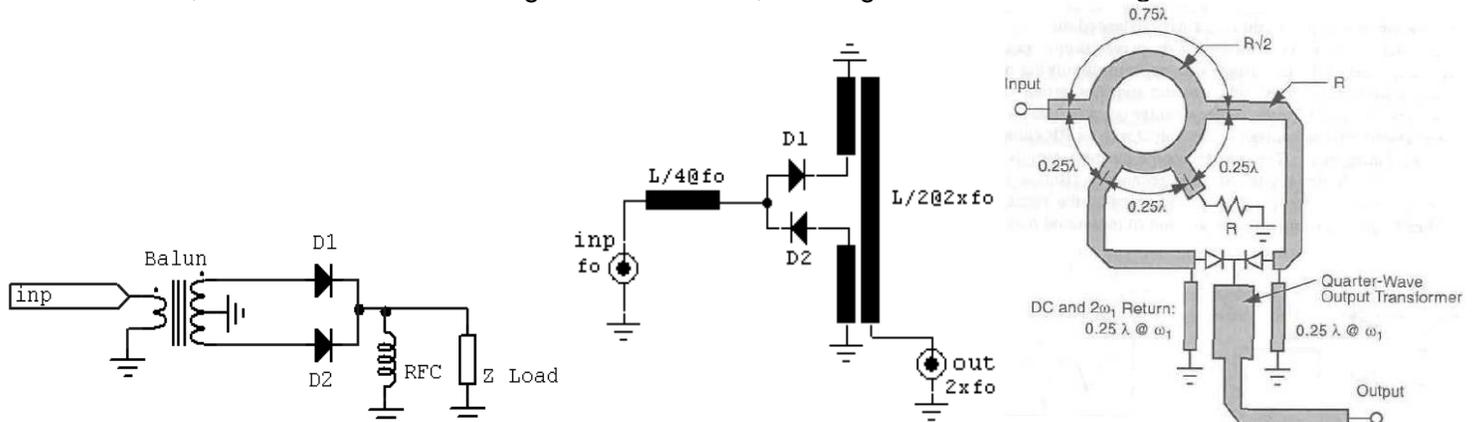


x5 Frequency Multiplier using anti-parallel PIN diodes and output spectrum

The above circuit is an x5 multiplier operating from a 100 MHz input at +13 dBm, and frequency output at 500 MHz and level at about -6dBm. The input was matched with a shunt inductor, and other passive components were added to the output to provide filtering of unwanted signals.

Because the stability of a varactor multiplier is sensitive to small unbalance between the diodes, varactor multipliers are rarely realized as anti-parallel circuits.

The circuit below shows a single-balanced multiplier using a balun transformer. The difference compared to a DC power supply circuit (which looks like) is, that in a power supply we are looking only for DC component, filtering all the harmonics, when here we are looking for 2nd harmonic, shorting the DC current using an RF choke.



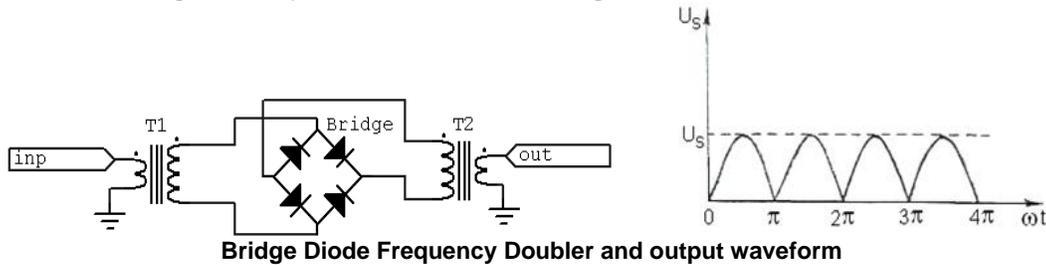
Single-Balanced frequency doublers using: Transformer Balun, Microstrip Balun, and Rat-Race Hybrid

The **Bridge Rectifier** circuit is a practical way to realize resistive frequency doublers.

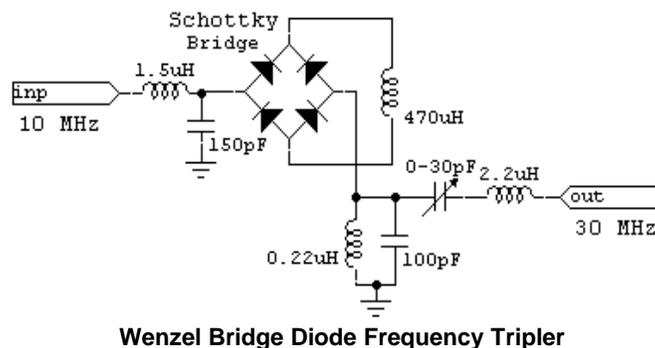
The design of these multipliers is not the same as the design of a diode ring mixer because the diodes are connected as in a different manner. The ring mixers require baluns when the bridge rectifier requires transformers.

The voltage and current waveforms in the balanced bridge multiplier are identical to those of a full-wave rectifier in a DC power supply. The current consists of a train of half-sinusoidal pulses, which has no odd harmonic components.

Thus, the multiplier inherently rejects the two most troublesome harmonics, the first and third, and the fourth is usually weak enough to require little or no filtering.



Charles Wenzel got an RF Design Award for the bridge frequency tripler presented below.



How the circuit works:

- The heart of the multiplier is a sinewave to square-wave converter circuit, which basically is simply a full-wave bridge diode (Schottky barrier) with an inductor short-circuiting the DC terminals.
- The inductor is chosen to have high impedance at the operating frequency so that an AC input results in DC in the inductor.
- This DC flows through alternate pairs of diodes due to the commuting action of the input voltage.
- Therefore, if one AC terminal of the bridge is driven with low impedance sinewave, the other AC terminal will supply a square-wave to a low impedance load.
- The load must have low impedance since the compliance of this current source is exactly equal to the input voltage.
- Because the diodes switch at the input signal's zero crossing the circuit introduce a minimum of AM/PM conversion.
- The input matching network it provides a low impedance to ground for the switching current; and it isolates the input from the switching current.
- The output network presents the required low impedance to the bridge while directing the desired harmonic to the output.
- The conversion efficiency is as high as diode frequency doublers, even though the multiplication factor is higher.

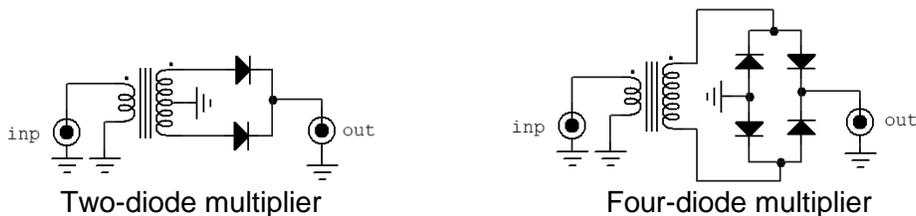
- Broadband FET frequency multipliers usually exhibit high conversion loss (about 10 dB, depending on the frequency range) and considerable passband ripple. They also generate substantial AM noise and, because they tend to amplify the input signal, often have poor fundamental-frequency rejection.

Schottky diodes do not have such severe inherent bandwidth limitations; however, there are three difficulties in the realization of such circuits as monolithic ICs:

- most conventional balun circuits are not planar.
- multipliers using Schottky diodes are usually limited in bandwidth by the multiplier's baluns.
- resistive doublers are subject to a high theoretical minimum conversion loss. The maximum efficiency achievable with a resistive multiplier is n^{-2} where n is the harmonic number. Thus, a resistive doubler can achieve no better than 6 dB conversion loss.

In practice, obtaining good conversion efficiency is difficult, and conversion loss below 10 dB is rarely achieved, even in narrowband circuits.

The **full-wave rectifier multipliers**, realized with either two or four diodes, are possible:



- The **two-diode circuit**, requires a current return through the center tap of the transformer. This would not be a problem if an ideal transformer could be used, but the residual inductance of a real transformer is in series with the output, and increases the loss. In microwave realizations, a planar balun is used instead of a transformer, and baluns do not have a center tap.
- The alternate **four-diode circuit** shown, does not require an output balun and as such appears to be superior to the circuit **Bridge Diode Frequency Doubler** shown previously. However, it has a problem: unless the even-mode output impedance of the balun is very high, the two diodes connected between the balun and ground are loaded by the balun. This unbalances the structure and degrades the fundamental-frequency rejection.
- The four-diode multiplier is especially well suited to microwave realization because no current return is needed in either of the baluns, and the impedances of the balun, source, and load resistances are usually easy to realize. The connection points of the input balun are virtual grounds for the output, and vice versa. Thus, good balance is assured.
- An advantage of the bridge rectifier is that it can be used when the input and output frequency ranges overlap. Fundamental-frequency rejection depends on the quality of the baluns; in particular, a high even mode impedance in the coupled-line sections is necessary.
- The design of a frequency multiplier requires the determination of the source and load impedances seen by the diodes. For a balanced multiplier, these can be found by reducing the circuit to a single-diode equivalent. In this type of multiplier, the source and load impedances of the single-diode equivalent circuit are fortuitously the same as those of the balanced multiplier, and are about 40 ohms.
To resonate the small junction capacitances of the diodes, the source and load impedances must have a small inductive component as well.

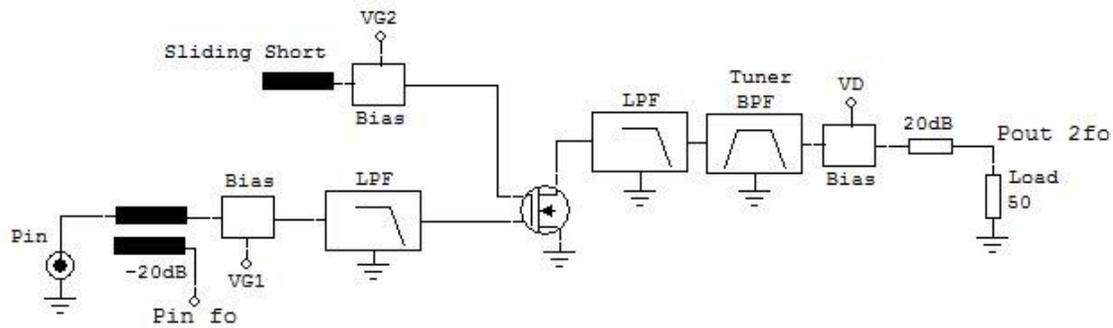
Active Frequency Multipliers

The main reason using active frequency multipliers is they got better efficiency compared to diode frequency multipliers, but at the expense, they have higher noise levels compared to diode multipliers. In contrast to diode multipliers which always exhibit loss, FETs or BJTs multipliers can achieve conversion gain over broad bandwidth while getting also good DC to RF efficiency.

The same as amplifiers the active frequency multipliers work in different classes.

A practical form for an active frequency multiplier is to operate in equivalent Class-B power class, where they are very stable and have good gain, efficiency, and output power.

- Unlike passive multipliers, active multipliers provide the possibility of conversion gain.
- FET devices are commonly used as the nonlinear device, and offer the advantage of possible integration into a single technology if monolithic implementation is required.
- The nonlinear mechanisms that can be utilized for harmonic generation are the nonlinear input gate source capacitor, C_{gs} , the nonlinear transconductance, g_m , the nonlinear output conductance, g_d , and the intentional clipping of the output drain-source current due to pinch-off and/or gate junction forward conduction.
- FET multipliers require much lower input drive levels compared to diode-based multipliers, are less sensitive to temperature variation, and are capable of wideband operation.
- The advantages of FET-based frequency multipliers over varactor-based multipliers were identified as achievable gain, wideband operation, better isolation, lower noise performance, and lower required input drive power.
- Common-source configuration gives higher gain compared to common-gate configuration.
- The chosen FET device is frequently a MESFET, HEMT or pHEMT, device with a cut-off frequency f_t , higher than that of the required harmonic.
- The input matching network presents harmonic terminations $\Gamma_s(f_0, 2f_0, ..)$, to typically present an optimum fundamental impedance which ensures maximum power transfer from the source to the input of the device and also provides appropriate termination to the remaining harmonics.
- The output matching network presents harmonic terminations $\Gamma_L(f_0, 2f_0, ..)$ to transform the 50 ohms load to the optimum impedance at the required harmonic and unwanted harmonics, in order to maximize the power of the former and provide suppression of the latter. The gate and drain of the device are typically biased through an RF choke and DC blocking capacitor. The bias levels coupled with the input and the output matching networks are designed to maximize the power of the required harmonic at the 50 ohms load.
- The harmonic content of the drain voltage and drain current are related to the bias supply.
- Was shown and verified that the primary method for second-harmonic generation using GaAs-FETs, for maximum conversion gain was obtain by clipping the drain current by biasing the gate at either pinch-off or junction forward conduction at 0V.
So, optimally biased FET multipliers near pinch-off that exploit the non-linearities generated through single-sided drain clipping, has come a classical frequency multiplier design.
- It was recognized that the short-circuit termination to all unwanted harmonics at the output, and the simple fundamental conjugate match at the input may not produce a multiplier with optimum operation. This led to the popular load/source -pull analysis for the design of frequency multipliers, where the bias levels and harmonic terminations at both the input and output of the active device are swept simultaneously to determine the optimum operating conditions.
- A dual-gate GaAs-FET can be used for frequency multiplication. This type of device was previously used in the design of mixers and variable-gain amplifiers that exploited the fact that the transconductance of the FET can be controlled by the voltage applied on the second-gate. The input drive was applied to the first-gate, and a sliding short is used at the second-gate to enhance the doubling frequency, as is shown in the picture below:

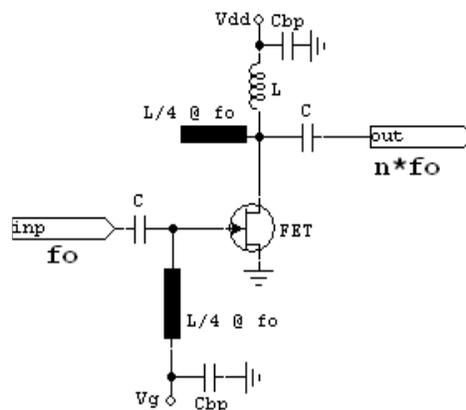


Dual-Gate FET frequency doubler test-setup

The output was coupled to an HPF to reject the fundamental frequency f_0 followed by a second harmonic tuner to maximize output power at $2f_0$. The gate and drain bias voltages are also varied to provide optimum conversion gain at each level of input drive.

- For example, using a dual-gate GaAs-FET and $f_0 = 6\text{GHz}$, a conversion gain of 8dB could be achieved at 12GHz with input power of 0dBm at f_0 .
A similar test-setup could also be used to investigate the tripling performance of the dual-gate GaAs-FET, and conversion gain of about 3dB could get at an output frequency of 12GHz, and about -2dB at 18GHz.
- An active FET frequency multiplier generates harmonics by rectifying the sinusoidal input signal when is biased near its turn-on point (pinch-off), and the input sinusoid turns the device on over part of its cycle.
- The condition is obtained by applying a positive drain voltage and a negative voltage to the gate. A practical application is to replace the negative supply to a self-bias source resistance, and a gate grounding resistor.
- The duty cycle of the input signal is adjusted to maximize the desired output harmonic.
- The higher the harmonic, the shorter the duty cycle must be.
- For a frequency doubler the optimum duty cycle is about 25% ($1/4$) when for a frequency tripler is about 16% ($1/6$).

Figure below shows the circuit of a basic broadband frequency multiplier that uses an ideal FET.



Broadband Active Frequency Multiplier (FET)

- The output resonator is tuned to the n^{th} harmonic of the excitation frequency, so it short circuits the FET's drain at other frequencies, especially the excitation frequency (f_0) by using an $\lambda/4$ open stub.
- The gate-bias voltage V_g in an efficient FET multiplier must be equal to or less than (more negative than) the threshold voltage, V_t . In this case the FET's channel conducts only during the positive half of the excitation cycle, and the drain conducts in pulses; the shape of the pulses is approximately a rectified cosine.

- The duty cycle of the pulses varies with the DC gate bias, V_g .
- If $V_g = V_t$ the duty cycle is 50%,
- If $V_g < V_t$ (the usual situation), the FET is turned off over most of the excitation cycle. The duty cycle in this case is less than 50%.
- If V_g is much smaller than V_t the magnitude of the peak reverse voltage establishes a limit on the difference.

The second important bias point (after Class-B) is with zero gate voltage, which sometimes is referred as Class-A multiplier. This bias point should give the same performance as the pinch-off, if the gate voltage swings from zero to pinch-off and a low-impedance is connected to the drain.

Microwave transistors are unconditionally stable only within certain frequency ranges, usually above a certain minimum frequency, and we know that the load termination at the fundamental frequency has a major effect on circuit stability.

- Because the load termination controls the series and parallel resonance of the transistor parasitics, and is controlling the peak of the rectified current or the distorted drain voltage, it will affect the multiplier gain, input impedance and bandwidth.
- The proper drain termination is the one that induces the highest peak current. This is obtained by short-circuit at the fundamental frequency. Ideally the load should be short circuit at all harmonic frequencies, but the presence of a load at a specific harmonic deviates the signal trajectory in the input plane and the load line becomes a function of frequency.
- Sometimes using other terminations, especially an open-circuit drain termination at the fundamental frequency, has advantages over a short circuit. The primary advantage of using other terminations is that greater gain can be achieved, although the increase in gain usually is the result of undesirable feedback and getting unpredictable oscillation.
- To get a good conversion gain the input power should not be very high. The required input power is proportional to square of f_0 (f_0^2), so the required input power increases 6 dB per octave; or, in other terms, the available gain decreases by 6 dB per octave. If the input is well matched across a broad bandwidth, a gain slope inevitably results.

The generation of harmonics using FET transistors can be done not only from current or voltage clipping, but also due to mixing of fundamental frequency, and any one of the generated harmonics.

One way to use mixing is to reflect all generated harmonics back to the drain and the other is to feed them back to the gate.

- The initial step in an active multiplier design is to find the performances of the active device at fundamental frequency, looking to parameters as: transconductance g_m , transition frequency f_t , and the maximum oscillation frequency f_{max} .
- The transconductance (g_m) has a direct impact in the device's power performance and multiplication gain, and f_t and f_{max} determined the limits to be used as a frequency multiplier.

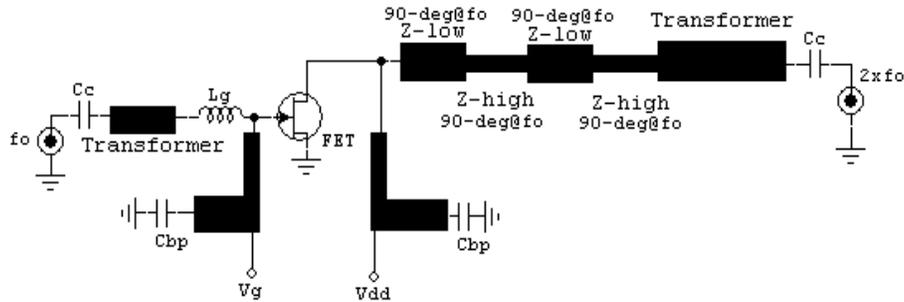
Harmonic Load Pull Test

This is a method which employs no device model and is essentially an experimental process. This method is very useful designing a nonlinear frequency multiplier.

- The active device is inserted into a circuit that has the input tuned at the fundamental frequency and the output tuned at the desired harmonic frequency.
- The active device is then removed and the matching networks are measured using a Vector Network Analyzer, getting the desired impedances which to be applied to the device.
- After that, a conventional linear simulator could be used to synthesize the matching network.

Frequency FET Doublers

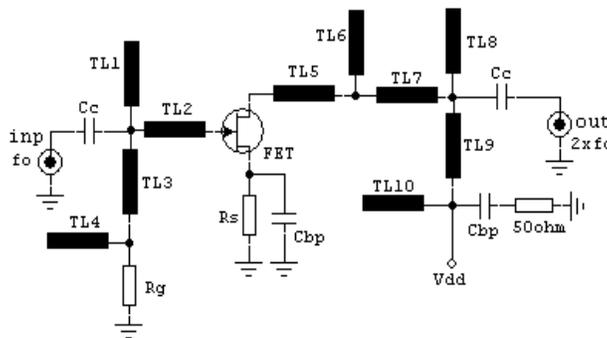
Below is presented a **High-Frequency Doubler** using a high frequency FET transistor.



High-Frequency FET Doubler

- To get good input VSWR and maximum power transfer, the input is conjugate matched using microstrip distributed and lumped elements.
- For moderate bandwidth (less than 30% of the center frequency), can resonate the input capacitance with a series inductor. For uniform conversion gain may need to match the input best at highest frequency of the band.
- The output matching network it consists of a filter, to short-circuit the drain at the fundamental frequency and unwanted harmonics, followed by a matching transformer.
- A half-wave filter is ideal for the output; it consists of a cascade of alternating high- and low-impedance transmission-line sections, each $\lambda/4$ long at f_0 ; these sections are $\lambda/2$ long at $2 \cdot f_0$ and $3\lambda/4$ long at $3 \cdot f_0$. So, the frequencies of maximum rejection occur at f_0 and $3 \cdot f_0$, but the filter has no rejection at the output frequency $2 \cdot f_0$.
- The imperfect output termination could make the multiplier unstable and cause fundamental frequency leakage.

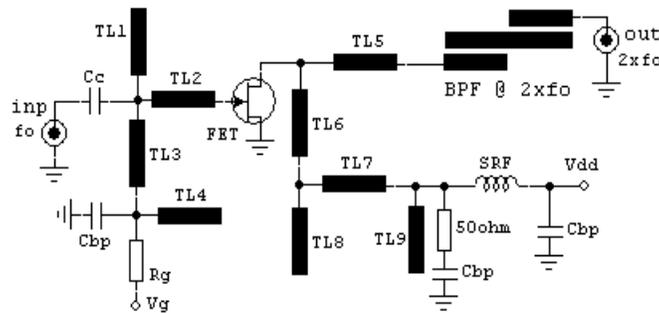
The **Narrow-band Frequency Doubler** presented below contains the matching transmission line elements TL1 and TL2, and the bias filter elements TL3 and TL4.



Single Ended Frequency Doubler – Narrowband

- The drain circuit use the transmission line phase-shifter TL5 to adjust the phase of the fundamental frequency impedance, and a harmonic band pass filter.
- The output BPF it is composed of $\lambda/4$ transmission lines TL6, TL7 and TL8, which block the fundamental frequency and the 3rd harmonic, and present 50 ohms termination at the 2nd harmonic.
- The electrical angles (phase) of the gate and drain transmission lines, TL5 and TL6, affect the multiplication gain up to 3dB.
- The drain bias filter is composed of elements TL9 and TL10 and their function is to isolate the bias from the generated 2nd harmonic.
- The RC circuit in parallel with the power supply is for overall stabilization.

The **Wide-band Frequency Doubler** presented below use a transmission line (TL5) in series with the output BPF to adjust the phase of the impedance at the fundamental frequency.



Single Ended Frequency Doubler - Wideband

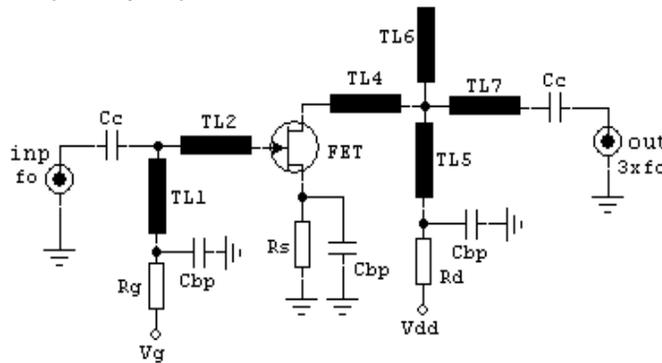
The BPF rejects the fundamental and the 3rd harmonic frequencies. There is also a band-stop filter (TL7, TL8, TL9) which blocks the 2nd harmonic, and presents low-loss at fundamental and 3rd harmonic.

Frequency FET Triplers

An important difficulty in frequency triplers is the need to short circuit the drain at the unwanted harmonics.

- For example, a frequency doubler is easy to do using a $\lambda/4$ stub, which effectively shorts the first and third harmonic, while the fourth and higher harmonics are weak enough to neglect. But is not very simple for terminating the drain in a frequency tripler.
- The output network can be difficult to design; the inevitable result is a suboptimum termination, which makes very hard to optimize efficiency and get the risk of instability.

This is an example of a FET frequency tripler:



FET Frequency Tripler

- The input stub, grounded at high frequencies by a capacitor, provides a match for the fundamental input frequency, while in the same time it facilitates bias injection at the gate of the FET device by providing some decoupling.
- The bias scheme adopted for the frequency tripler was a self-bias arrangement with resistor between source and ground. Such a self-bias configuration tends to bias a FET device towards pinch-off, with the resistor value determining how close the device is to pinch-off. The larger the value of the closer the bias point is to pinch-off. If the gate bias is connected to an external supply, an option effectively to over-write the self-bias setup is made available.
- At the output, a double stub arrangement has been placed. These stubs get multiple functions. First, they form an output match for the desired 3rd harmonic signal. Secondly, they implement some filtering of undesirable fundamental and 2nd harmonic leakage to the output. Using here the real-life stubs, it can be difficult to filter the fundamental without rejecting the desired 3rd harmonic at the same time. This happened when considers the simplest stub arrangement to reject the fundamental, which is an open circuit $\lambda/4$ stub. However, such a stub is long $3\lambda/4$ at the 3rd harmonic and tends to reject this frequency as well. As a consequence, the design of the output

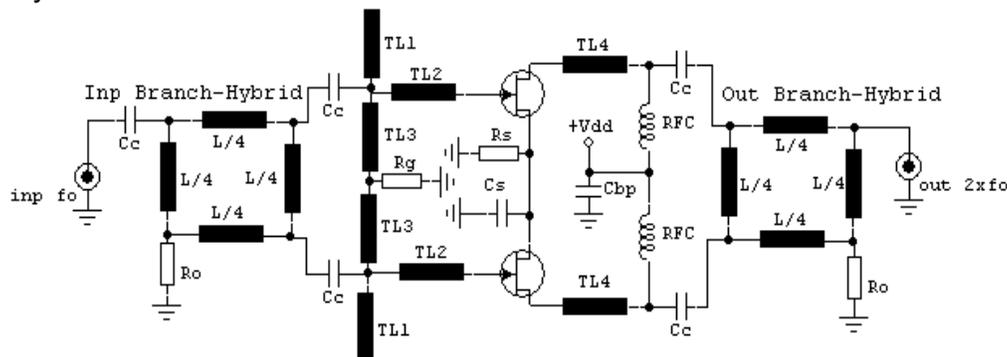
stub pair involved a compromise in terms of fundamental and 2nd harmonic rejection, without excessively loading the 3rd harmonic response.

- The output stubs is essentially a short circuit stub, the high frequency short being provided by a capacitor to ground. This stub also facilitates drain bias injection.

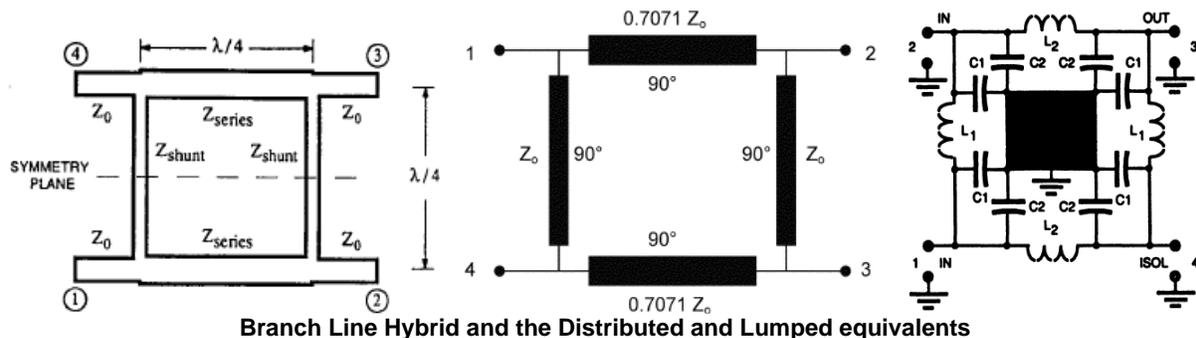
Balanced Frequency Multipliers

Reasons using of Balanced Frequency Multipliers are:

- they have improved input match over wide bandwidth,
- they have good isolation between multiplier stages,
- they are very stable since the device is terminated in 50 ohms over a wideband frequency.



Balanced Frequency Doubler using Branch Line Hybrids



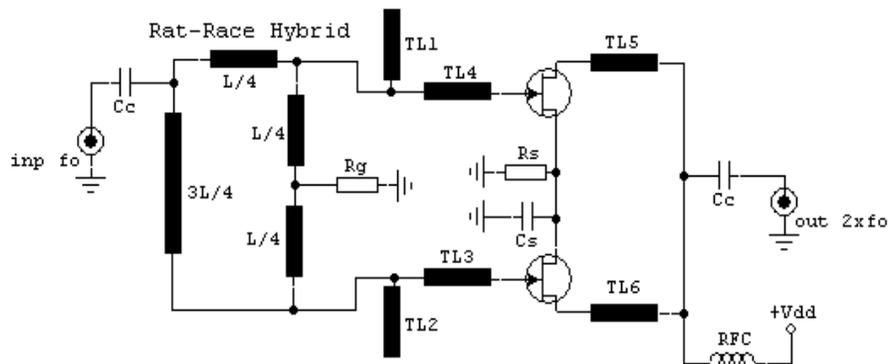
Branch Line Hybrid and the Distributed and Lumped equivalents

- The input hybrid coupler introduces a 90° phase shift and the output hybrid another 90°.
- Therefore, the odd harmonics are 180° out of phase, are cancelled at the output port, and dissipated at the coupler termination.
- The even harmonics at the output port are in phase and added in power.
- A balanced multiplier has 3dB greater output power than an equivalent single-device circuit.
- The main bandwidth limitation is given by the FETs input and output matching networks not matched for wideband response.
- The circuit is self-biased using TL3 and Rg gate to the ground and Rs as source resistor. The bias is chosen to be near pinch-off point.

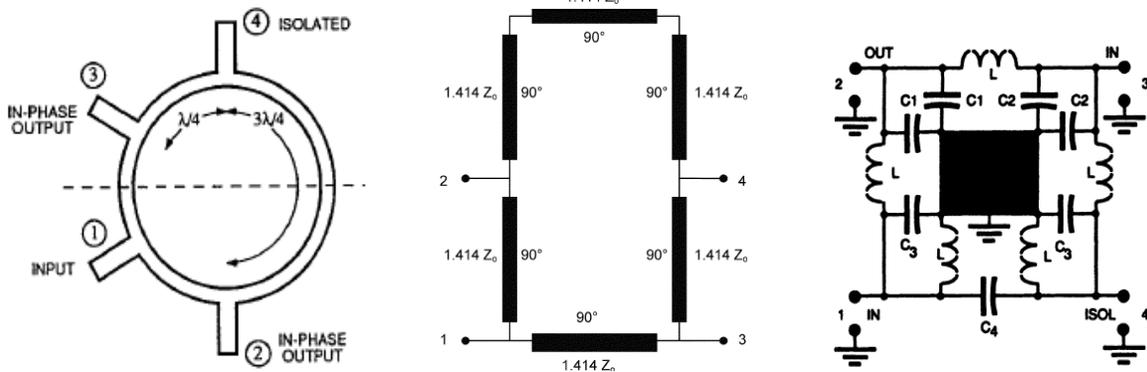
Balanced to Unbalanced Frequency Doubler

Another option is to use only at the input a 180° Rat-Race hybrid to drive each device in anti-phase.

- In this way the fundamental drain currents are also in anti-phase and good rejection is obtained by paralleling both drains, and the drain connection point becomes a virtual ground for fundamental and for all odd harmonics.
- The even harmonics of the drain currents in the two FETs have no phase difference, however, so the drain-current components at those frequencies combine in phase at the output.



Balanced to Unbalanced Frequency Doubler using Rat-Race Hybrid

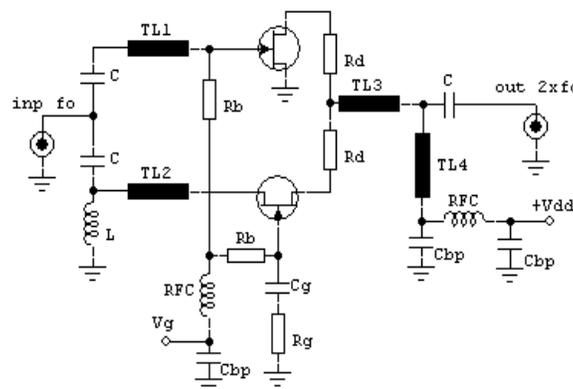


Rat-Race Hybrid, and its Distributed and Lumped equivalents

- To get a constant gain at the output, the gates matching networks are designed for maximum gain at fundamental high-end and around 3dB less gain at the low-end of the useful band.
- The disadvantage of this topology is sensitivity to device DC imbalances and input matching networks, compared to the balanced multiplier using hybrids at both, input and output.
- Any imbalance is reflected back to the generator requiring an attenuator at the input to minimize the resulting standing wave.

Balanced Frequency Doubler using Active Balun

The frequency doubler using an active balun presented below is suitable for small size circuits, replacing the passive balun topologies.



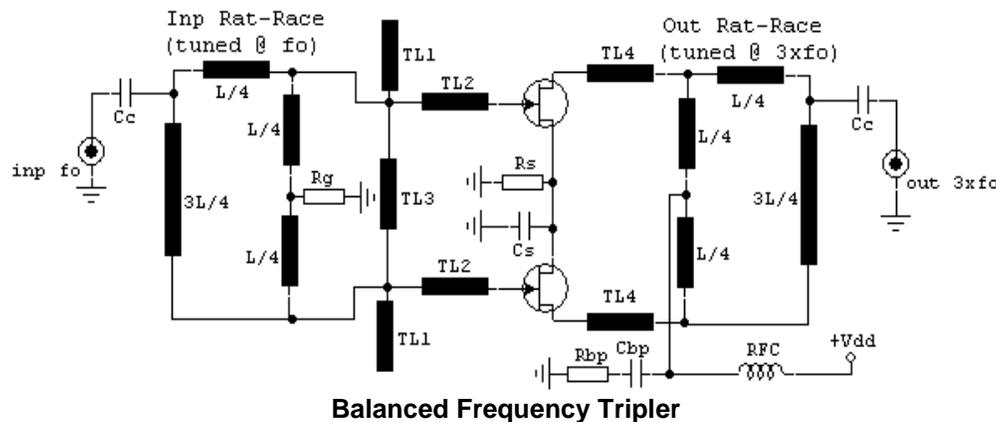
Balanced Frequency Doubler using Active Balun

In this frequency doubler, a simple combination of Common-Gate FET and Common-Source FET provides the required 180° phase difference for the cancellation of the fundamental.

- This active balun has the advantage getting small size at low frequencies.
- The stability has to be controlled, in contrast to a passive balun, and the circuit should be unconditionally stable for all input impedance attached.

- To get unconditional stability and to avoid negative resistances at gate and drain of the Common-Gate FET, a series resistance R_g , is added to gate. This reduces the gain, but it improves stability by decreasing the loop gain at the same time. In addition, two series resistors R_d are added in both drain connectors to decrease the loop gain.
- The frequency doubler has a short-circuited stub TL_4 and a series transmission line TL_3 for an output impedance adjustment at the connection of the two drains. These elements provide a short for the fundamental and additional match for the 2nd harmonic.
- The bias point was chosen at $V_g=0$ to obtain high fundamental suppression and 2nd harmonic.

Balanced Frequency Tripler



- The input match is made with open-circuited stubs TL_1 , and high-impedance lines TL_2 .
- The $\lambda/4$ TL_3 connecting both inputs introduces a short at the 2nd harmonic, improving the performance.
- The output match contains only a $\lambda/4$ high impedance transmission lines TL_4 , to parallel tune the drain output impedance at the fundamental frequency.
- The device is self-biased and the source resistor R_s is decoupled with C_s .

Higher Order FET Frequency Multipliers

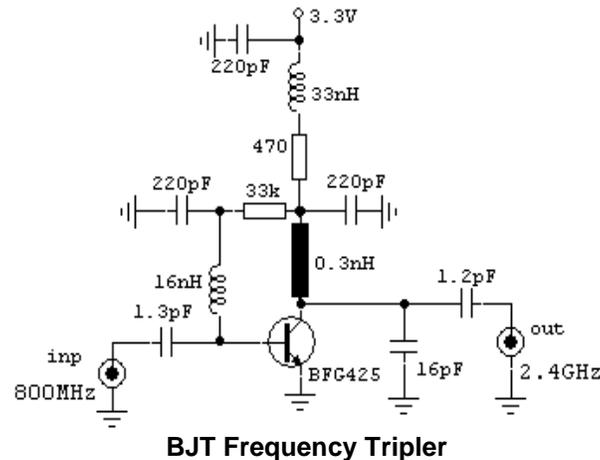
- The direct generation of harmonics of higher order can be obtained by biasing the device at different conduction angles.
- For even order the device is biased in Class-AB similar for frequency doubler, in order to maintain a rectified sinusoidal drain current which is rich in even harmonics.
- For odd order harmonics the optimum bias condition is the one that generates an output waveform with distorted positive and negative peaks. The first option would be to bias the device in Class-A, about the center of the drain current, and apply a high power at the gate.
- The magnitude of higher harmonic components like 5th, 6th, 7th, etc, becomes too small, requiring a high load resistance to compensate the reduction in output power.

BJT Frequency Multipliers

The theory of bipolar multipliers is essentially the same as that of FET multipliers. A few notes on the differences, however, are in order.

- Unlike FETs, whose channel currents are limited to a little over I_{dss} , bipolar devices do not have such a strict limit.
- Their operation is based on the nonlinear capacitive reactance of the reverse-biased base-collector junction.

- Silicon BJTs experience high-level injection effects, which tend to limit the peak current and reduce transconductance at high collector current.
- Bipolar devices have a large, strongly nonlinear base-to-emitter capacitance. Because of that capacitance, BJT multipliers are susceptible to modes of oscillation that are not unlike those of junction varactor multipliers for example. As with varactors, the best (and simplest) way to avoid such instability is to short-circuit the base and drain at all unwanted harmonics. Have to verify also that active DC bias supplies do not exhibit negative resistance or couple the collector to the base at low frequencies.
- Because multiplying devices are turned off under quiescent conditions, BJT multipliers should not be current-biased; they must be biased from a voltage source, ideally with a series resistance.



Active Frequency Multipliers - Terms and Quantities

- The important performance parameters for an active frequency multiplier are its output power, gain, DC-to-RF efficiency, power added efficiency, and harmonic rejection.
- The **conversion gain** is defined by the ratio of output power at the required harmonic and the available input power at the fundamental frequency:

$$\text{Gain} = P_{\text{out}}(N f_0) / P_{\text{in}}(f_0)$$

- The **DC-to-RF efficiency** is a measure of the amount of DC power that is converted to RF power at the desired frequency, and is defined as the ratio of output power at the required harmonic N and the DC power consumption:

$$\eta_{\text{DC/RF}} = P_{\text{out}}(N f_0) / P_{\text{DC}}$$

- **Power Added Efficiency (PAE)** is the ratio of the difference in output and input RF power to the total DC power consumption:

$$\text{PAE} = [P_{\text{out}}(N f_0) - P_{\text{in}}(f_0)] / P_{\text{DC}}$$

- Another useful measure is the **overall efficiency**, which incorporates the total amount of power injected into circuit and the amount of output power obtained at the required harmonic N:

$$\eta_{\text{overall}} = P_{\text{out}}(N f_0) / [P_{\text{in}}(f_0) + P_{\text{DC}}]$$

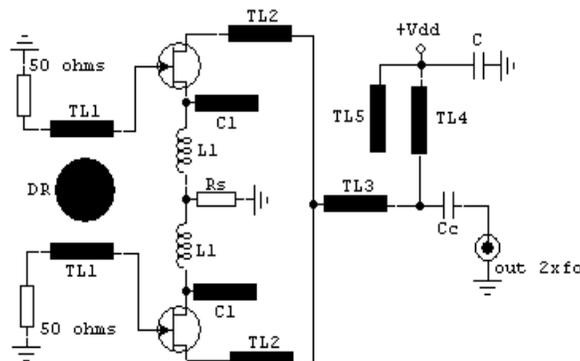
- The term **conversion efficiency** is the conversion gain expressed in percentage, with percentage lower than 100% implying a conversion loss.

- **Harmonic rejection** is another important figure of merit in the design of frequency multipliers. It is a measure of the difference in power level between the wanted and the unwanted harmonics, and is expressed in dBc. Improved harmonic rejection is achieved through appropriate harmonic terminations at the ports of the device, with optimum design providing reactive terminations to the unwanted harmonics in order to maximize the conversion gain of the frequency multiplier.

Balanced Push-Push Harmonic Oscillator

Another option generating high frequency signal, using most of the characteristics of the frequency multipliers, is the Harmonic Oscillator.

Below is presented an example of a balanced harmonic oscillator.



Balanced Push-Push Harmonic Oscillator

- The push-push harmonic oscillator employing two transistors, each oscillating at one half the desired output frequency.
- The transistors oscillate out-of-phase with respect to each other, causing the fundamental frequency to cancel and the second harmonic to add in phase.
- Push-push designs have several advantages over other topologies. Designing at one half the frequency increases resonator Q, decreases the parasitics which appear, and extends the useful frequency range of transistors.
- The dielectric resonator is placed between the two gates transmission lines (TL1)
- Biasing the circuit in Class-AB, guaranties the start-up and stable oscillation, and also the generation of even harmonics at the output.

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